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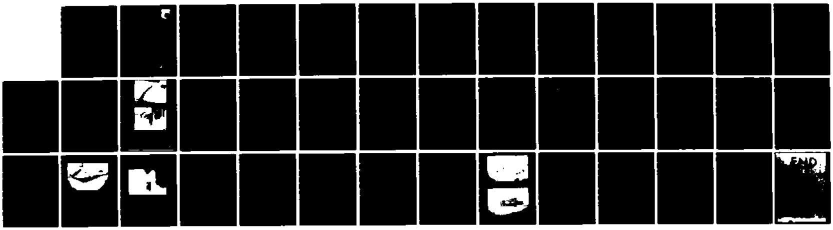

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END-POINT CONTROL OF FLEXIBLE ROBOTS

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August 1984

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The objectives covered herein were: "first, to significantly increase the speed and precision of performing "slew and touch" tasks for a flexible robot arm and second, to develop a universal robot end effector, capable of performing generic manipulation functions.

~~Our~~ The research concerns key technologies for new classes of robots capable of assembly with force control and great dexterity.

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We have built a dextrous, three finger hand, and have designed and implemented a force control system for it which will support dexterity. The system is novel in that it controls position, orientation, and forces exerted on an object. Commanding object motion instead of joint motion is natural for high level, task-oriented planning systems. The control system has a three level hierarchy, namely hand level, finger level, and joint level.

We have made progress toward an intelligent system for grasping objects and manipulating them without models of the object, and toward a system which uses object models in identifying objects and orienting them in grasping.

We have also achieved end-point control of a very flexible arm, and have demonstrated fast-slew-and-touch motions and the ability to maintain controlled forces at the arm tip using tip-force sensing to control shoulder torques. To do so, we have built a new flexible arm that can be controlled using optical tip-position sensing as well as tip-force sensing, and have investigated and implemented a switching method between position and force control when contact is made. A new, two-link rigid arm with flexible tendons was also designed, and its fabrication is now complete.

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INTRODUCTION

This report describes progress in research on intelligent sensory control of end effectors and manipulators. This is a joint research program between the Robotics Laboratory of the Stanford Artificial Intelligence Laboratory (SAIL) and the Guidance and Control Laboratory of Stanford's Aeronautics and Astronautics Department. The joint program operates within the Center for Automation and Manufacturing Science (CAMS).

SAIL reports progress on fabrication of a three finger hand with sensors, on sensory control of the hand, on intelligent task execution with the hand, and on sensor technology. The Guidance and Control Laboratory describes progress in force control and fast-slew-and-touch with very flexible manipulators.

These elements of task execution can be termed intelligence, skill, dexterity, and control, going from high-level planning strategy to servo level control. The research addresses three major advances in robots, first force control, second dexterity, and third carrying heavier loads at higher speed. The next major development in industrial robots is likely to be force control, especially in assembly. Robots in industry and in most research laboratories have position control of gross motion, not force control for fine motions in parts mating. The two programs in this joint effort study different aspects of force control of robots, in making contact with objects, in exerting controlled forces on objects, and in making constrained motions in parts mating for assembly.

Industrial robots and most robots in research laboratories have hands like pliers, i.e. two jaws without sensors with only a single degree of freedom. They cannot grip many objects in many positions, or make stable grasps, or adapt to incomplete information about position and orientation in grasping. Three fingers with the necessary freedoms and with force sensing support grasping curved objects in many positions, grasping them stably, adaptive grasping, re-orienting objects, and fine motion for parts mating and force control.

We study intelligence in grasping strategies and in parts identification by grasping.

We also study control methods which can contribute to lowering the cost of using robots by making them fast and increasing their payload despite limited strength and despite flexibility. Current robots are made stiff enough and strong enough to ignore loads. A Unimation PUMA weighs 120 pounds and carries a payload of five pounds. Unavoidable flexibility in drive trains of robots and in their mounts make control of flexible robots an important issue.

During the first year of the contract, our progress on intelligence and force control of dextrous hands includes:

1. Building a three finger hand with great dexterity; it has nine degrees of freedom [Salisbury 81];

2. Interfacing the hand to control computers;

3. Analyzing and implementing a force control system for the hand, with a three level hierarchy, hand level, finger level, and joint level [Salisbury 81]; shortly after the time period of this report, coordinated three finger motion was demonstrated;

4. Fabricating force-sensing fingers to measure three components of force;

5. Designing and building intelligent systems for identifying objects and orienting them in grasping, using object models;

6. Analyzing and developing methods for adaptive grasping of objects without object models; soon after the period of this report, we demonstrated rolling an object between two fingers.

Progress on force control and fast-slew-and touch motions of flexible manipulators includes:

1. Controlling force, position, and slew-and-touch motions for a very flexible arm:

1.a Designing, building, and interfacing a new flexible arm;

1.b Defining a force controller for contact;

1.c Switching between position and force control when contact is made.

2. Designing a new two-link rigid arm with flexible tendon drives. Fabrication is underway.

AN OVERVIEW

Intelligence and Force Control of Dextrous Hands

This research is aimed at understanding and developing motion capabilities in generic assembly operations which include: 1. tool using; 2. parts acquisition; 3. parts handling; 4. parts mating. Force control and compliance are crucial in generic assembly operations. These generic assembly operations depend upon generic motion capabilities which include: 1. grasping securely; 2. repositioning objects; 3. controlling and exerting delicate forces; 4. making fine motions.

Secure grasping is important for tool using and for rapid motion. A hand with parallel jaws can grasp an object in only a few configurations, e.g. at parallel faces. The three finger hand with nine degrees of freedom can grasp a broad class of objects in a range of configurations. Also, a hand with two parallel jaws can supply very little torque about the axis between the jaws. Thus, an object swings easily about this axis when moved rapidly or under small external forces. A three finger hand can supply the necessary torque to stabilize objects in rapid manipulation. After an early assembly of an electric motor, we set out to speed up and analyze the assembly. We achieved assembly in about 35 percent more time than a human. Insecure grasp limited the speed at which motions could be made without causing objects to swing. Two other operations were found to be slow, namely grasping and sensory operations.

In parts acquisition, e.g. bin picking, it is often necessary to grasp objects then reposition them for assembly. Two finger hands with one degree of freedom are kinematically incapable of repositioning objects. The three finger hand was designed with the degrees of freedom necessary to reposition objects fully in space, i.e. to rotate and translate them.

In force control, not only is force sensing important, but the device itself must be capable of fine force control. Fine motion devices provide the fine control which is not possible to achieve by working with the large joints of the arm. Humans typically perform fine operations by resting their wrist on a flat surface and acting with the fine motions of the hand, rather than working from the shoulder and compensating for the weight of the arm. The hand is instrumented to sense tendon tensions and to compensate for friction. Friction is a major obstacle in controllability. The hand was designed for fine motion. It was also designed to minimize friction by a pull-pull tendon design.

The hand provides fine motion to respond rapidly with small motions to accomodate errors measured with visual sensors and force sensors in close tolerance work.

The Intelligent Task Automation project carried out in collaboration with Honeywell, SRI, and Adept Technology, has already provided a way of technology transfer for force sensing fingers, for force control, and for fine motion strategies. The research also contributes to collaboration with MIT AI Lab in advanced hands and arms.

Rapid, Precise Position and Force Control of Flexible Manipulators

Manipulators — arms and hands with their actuators, and the increasingly sophisticated feedback systems that control their movements — are the "business end" of a robot,

(a) Very flexible one-link manipulator
(Rapid pick and place)

(b) Very flexible manipulator with force control
(Slew and touch moving target)

(c) Flexible manipulator with fast wrist
(Precise snatch and place)

(d) Two-link Arm with Elastic Tendons
(2D pick and place)

(e) Cooperating Two-Link Arms
("Long-Part" handling)

(f) Two-Link Arm with Double Wrist
(Very fast, precise 2D tasks)

(g) Two-Flexible-Link Arm

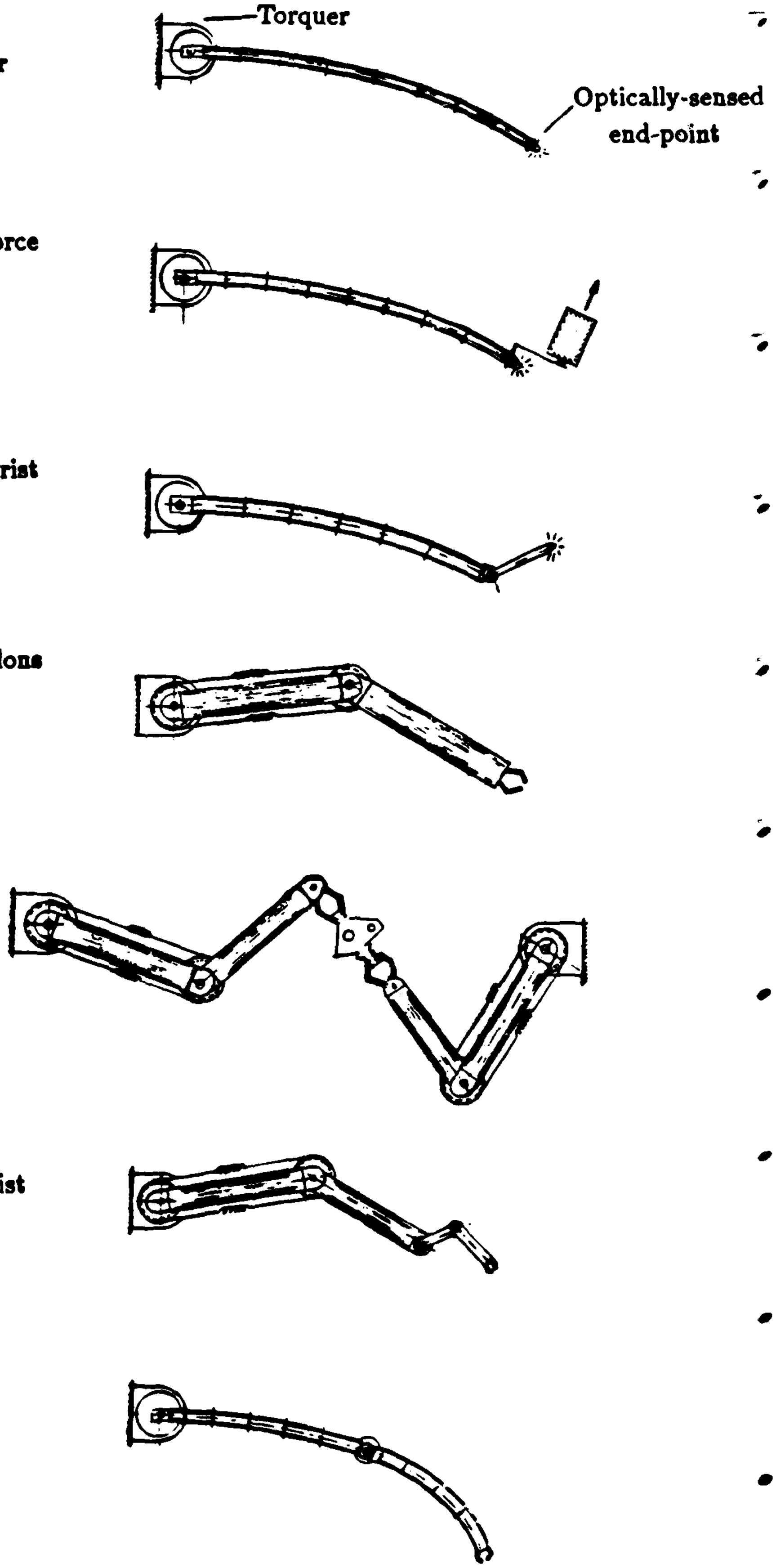


Figure 1. The Family of Flexible Manipulator Experimental Systems.

where parts are mechanically moved, formed, placed, fitted together (or dismantled), and inspected. In our Controls Group we are addressing the question of how to provide manipulator control so good that a whole new generation of manipulators can be developed — manipulators that are much lighter and far more facile than anything today's control systems could stably manage.

To do this we have begun to develop a sequential family of new manipulators that are extremely light and flexible, deliberately exaggerating the control problem so that it will have to be solved in much more fundamental ways than it ever was before. Some members of our family of manipulators are shown in Fig. 1. The family will also of course extend in many ways not shown — to three dimensional action, and to mobile-mounted very flexible manipulator systems, for example.

The central control problem for each of these manipulator systems — and the problem we have been the first to solve — is the problem of controlling the end-point (fingertips) of a manipulator by measuring position or force *at that point* and using *that* measurement to control torque at an actuator at the other end (elbow or shoulder) of the flexible manipulator. This turns out to be, for fundamental stability reasons, *very hard to do.* Every time someone has tried it (this *noncolocated* control) in commercial robots, the robot system has gone unstable.

Using advanced control methods developed in our laboratory we have already succeeded in achieving, for the first three configurations of Fig. 1, control that is not only stable but highly robust, and at a speed limited basically by wave propagation times in the manipulators themselves. By proceeding step-wise with the sequence of basic manipulator control problems indicated in Fig. 1, we expect to provide the fundamental new technology for controlling a new generation of lightweight flexible robots. The achievement of near-wave-propagation-speed control for the system in Fig. 1(a) was by Eric Schmitz, under NASA funding, and for Fig. 1(b) by James Maples, under this DARPA funding. Maples is concentrating on force control and fast-slew-and-touch control.

We are pursuing this force-control capability as part of a larger family of research on precise control of flexible manipulators under funding of DARPA, AFOSR, and NASA. The AFOSR research concentrates on establishing fundamental control relationships and limitations, while the DARPA effort is directed toward demonstrations and techniques of a synthesized nature for possible use by designers. The NASA work on flexible manipulators is directed toward activity in space — operations with systems like the Shuttle RMS, for example.

The interactions between our projects in control of flexible manipulators are many and the synergism is great, as we delineate in Fig. 2. Each box in Fig. 2 (e.g., "Very Flexible Arm with Tip-Force Control") is a major experimental configuration on which a sequence of new control capabilities is being (or will be) developed. The double solid boxes are AFOSR funded projects, and the double dashed boxes are DARPA projects. Each new capability (e.g., "Contact Force Control") achieved with a given configuration is invariably based on extending what was learned first with an earlier, simpler configuration; each of these new capabilities will be crucial to several that follow. Thus, the DARPA funding allowed us this year to bring the flexible manipulator with tip force control configuration from first conception through design and fabrication and assembly to a working system on which

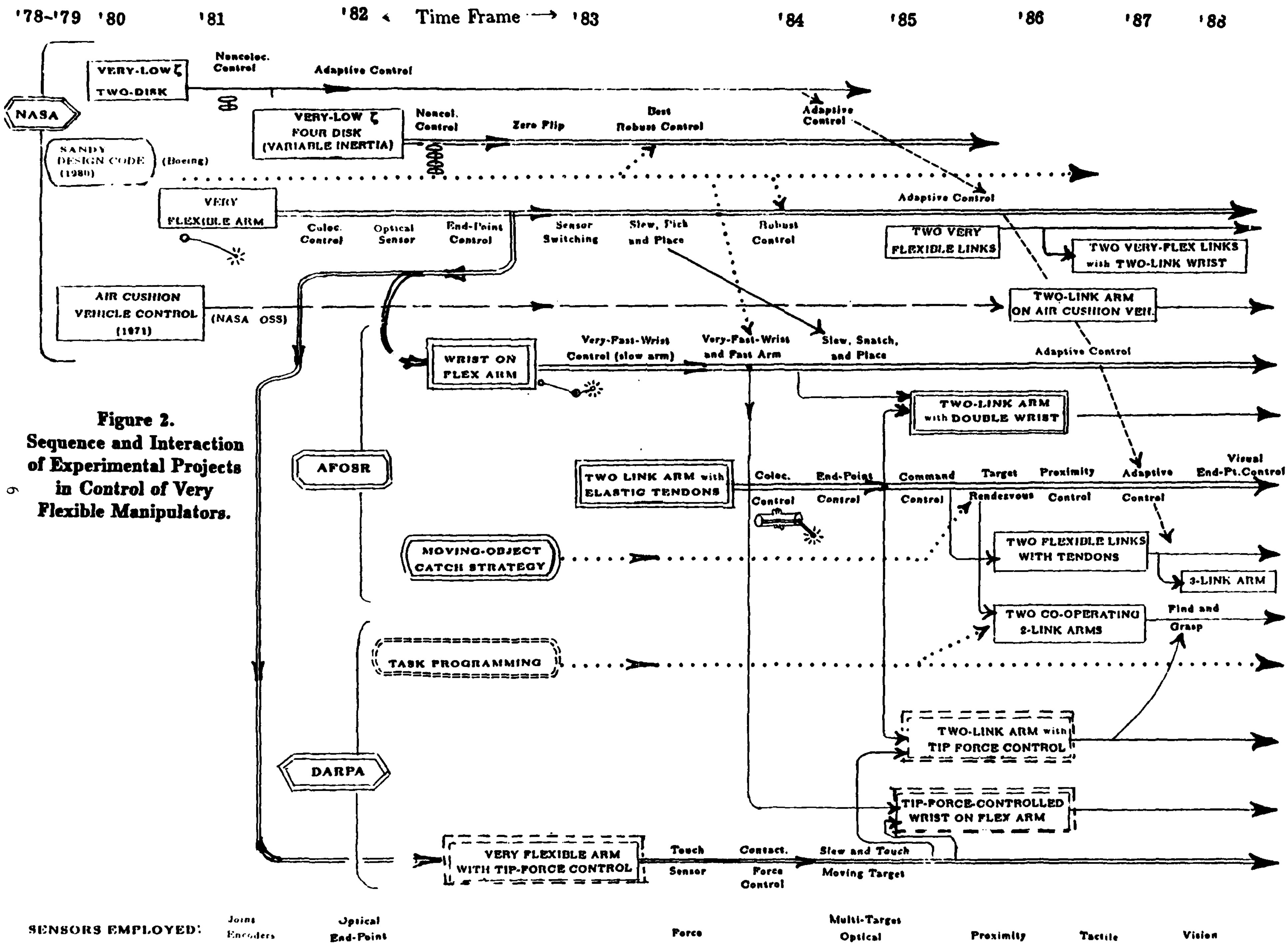


Figure 2.
Sequence and Interaction of Experimental Projects in Control of Very Flexible Manipulators.

early successful experiments with end-point control have already been accomplished. But this rapid progress was based firmly on the earlier step-by-step development of the single very-flexible manipulator, with its optical tip-position sensor and its pioneering end-point feedback control. (And that control, in turn, was able to draw on the earlier achievement of noncolocated control of the very-low-ζ disk system.)

In the future, the capabilities — of end-point force control using two actuators in concert and of obtaining coarse-fine precision — that will be developed first for the flexible arm with wrist, will then form the technical base for the major series of developments planned with the new two-link manipulator facility: experiments with control in two dimensions, with first optical, then force control; experiments with two arms plus double wrist; experiments with target tracking and rendezvous leading to a *pair* of two-link manipulators cooperating to perform higher-level tasks. Note that both well-developed force control (of a flexible manipulator tip) and task programming will be essential supporting capabilities at this point; they will be available from other, concurrent projects, as Fig. 2 shows.

As Fig. 2 indicates, the Two-Link Manipulator that we have designed and built this year with DARPA and AFOSR support will be (with its derivatives and augmentation) a major facility for a sequence of developments and demonstrations that will make more directly usable, by robot designers, the quite fundamental control advances we have been able to achieve.

A most important fact is that the gratifyingly rapid progress we have been able to achieve in each of the projects in Fig. 2 is due in great measure to synergism with the *other concurrent* projects in whose midst it exists. ***The combination of major funding indicated in Fig. 2 has made possible a critical mass of talented people and new equipment and activity, without which many of the achievements of this year would simply not have occurred at all, let alone so quickly. The presence concurrently of all these people is what has made these achievements happen.***

Again, the basic generic thing that we have been able to do (and be the first to do) is control very light, flexible manipulators in swift, purposeful motions: control position and force at their tips by measuring these quantities directly and feeding them back. As the sequence of projected project milestones in Fig. 2 unfolds, we aim to build a deliverable set of experimentally demonstrated fundamental robot-control-system design technologies that commercial designers can apply to the next much more capable generation of robotic systems.

This year with DARPA support we have made considerable progress in two areas:

(1) We have advanced our understanding and capabilities in *force control of a single, very flexible manipulator* to where we have achieved several goals listed under Tasks 1, 2, and 4 of our DARPA work statement.

(2) We have designed and constructed, with DARPA and AFOSR funding, a major new facility for our work: The Two-Link Arm with Flexible Tendons. Our experiments with it will provide major contributions to Task 3: ***Investigate new robotic arm designs.***

This facility will be used in the future for DARPA demonstrations. For the present, it has been turned over to more fundamental experiments under AFOSR sponsorship.

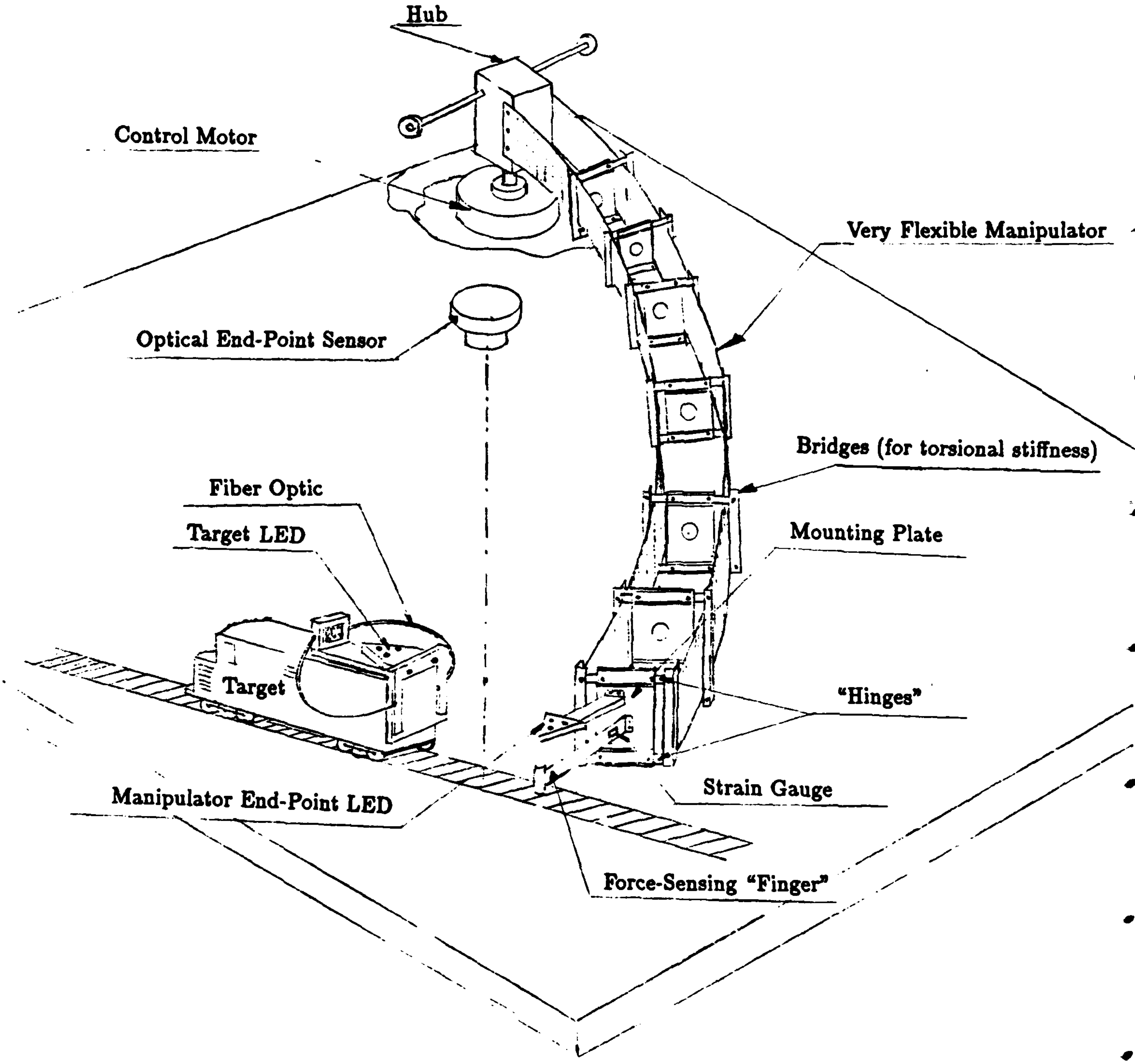


Fig. 3. Apparatus for Force Control of Very Flexible Manipulator.
Control motor is at far end. Sensor system is at near end. Optical photodetector is above LED's.

Force Control of Single, Very Flexible Manipulator

It is straightforward to discuss our progress in terms of the Task Statements of our contract. Tasks 1, 2, and 4 are discussed in this section. They concern (1) slew control to a target, (2) development of position (optical) and force sensors for the end-point of the very flexible manipulator arm, and (4) control of switching dynamics at the instant of contact with a target. We discuss first the new experimental system developed for Task 1, and the performance we have achieved to date in fast control of end-point position (Task 4.1.1.1), control of force, and control of the contact dynamics (Task 4.1.1.2 and 4.1.4.1).

We then discuss the underlying sensor developments (Task 2) that were necessary before Task 1 could be addressed.

Task 1: Control of Force, Position, and Slew-and-Touch Maneuvers

4.1.1.1 "Directing a highly flexible (0.5Hz), one degree of freedom, robotic arm, through a fast, large angle motion toward a target object."

While this project goal is listed as part of Task 1 of the contract, it is really one of the end results of our research, and requires first the completion of many of the other tasks. Our efforts over the past year have concentrated on constructing an improved hardware test bed for accomplishing this goal and, having done this, have now shifted to developing the required software control algorithms.

We have had in our laboratory, for some time, a flexible beam used in control system research. Our work with this beam (partially funded by NASA and AFOSR Contracts), had convinced us that updated hardware would greatly benefit our efforts. As a result, we have designed and built a new, second generation, very flexible manipulator. The new experimental system is shown in Figs. 3 and 4.

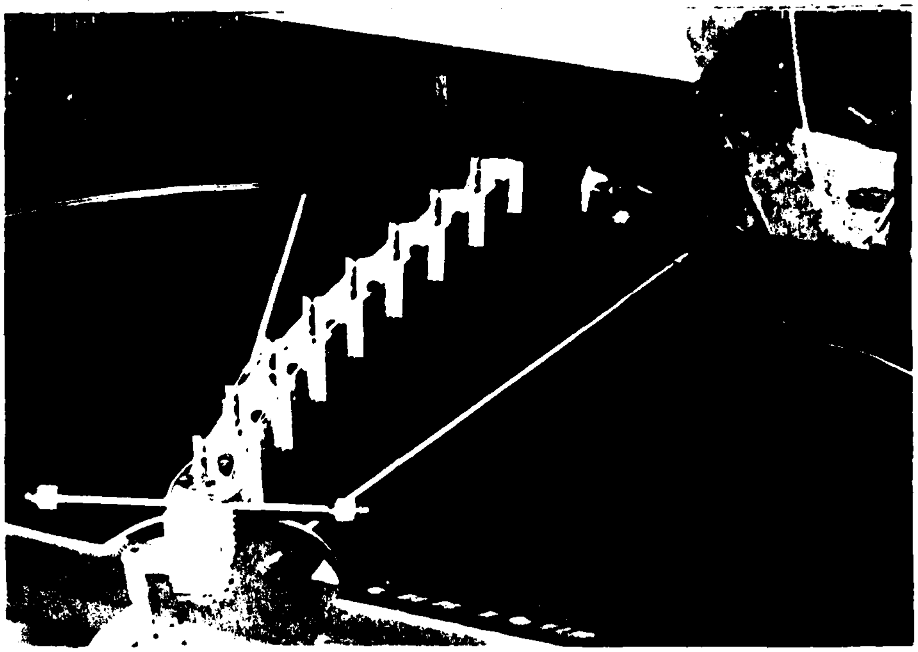
The manipulator itself consists of two parallel thin aluminum beams, connected by bridges to provide torsional stiffness, while permitting very flexible behavior in horizontal bending. At one end of the manipulator is a DC control motor, and at the *other* end are located the two primary sensors, one optical and one touch. Fig. 4(b) gives a closeup view of those sensors.

The new optical tip-position sensor consists of a set of three light-emitting diodes (LED's). Their emission is focused, by a lens, onto a photosensitive silicon detector which provides an analog voltage output proportional to spot location. (A hood, visible in Fig. 4(a), shields the photodetector from stray light.) Another LED set on the target is also visible in Fig. 4(b). The two LED sets can be flashed alternately at, say, 1 kHz, so that the photodetector can track and report simultaneously the position of both arm end-point and target. This is an important new capability for us.

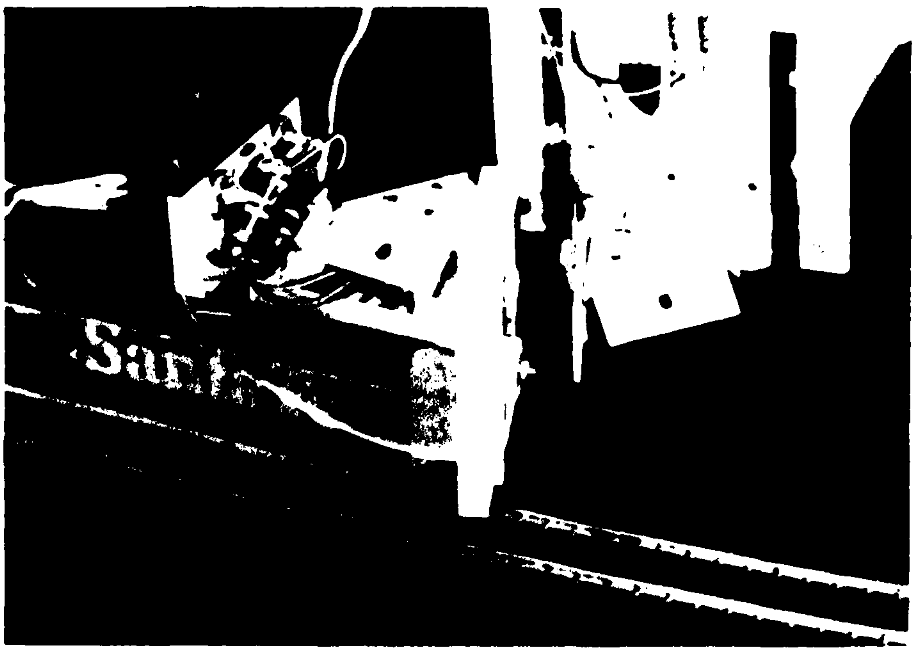
On the moving target we are using a fiber optics circuit (Fig. 3) to detect the exact moment of contact, to initiate switching from position control to force control. Fig. 4(b) shows also our first experimental sensor, a short cantilever "finger" (with teflon tip), with a strain gauge to report force.

Development of these sensors is reported in more detail under Task 2 below.

Some of the benefits of this new experimental design are that it:



(a.) Manipulator, under optical end-point control, nearing the end of its slew. The control motor (at near end) is "applying the breaks" as the manipulator tip nears the target.



(b.) Manipulator under force control. Force sensed by strain gauge on the "finger" is used to control torque in motor at the other end of flexible arm. LED's (triangles on arm tip and target) have now been switched out.

Fig. 4. SLEW AND TOUCH. Very flexible arm being slewed rapidly to target using (non collocated) optical LED sensors—one on the arm tip, one on the target—for control.

* retains approximately the same low transverse bending frequencies (the first is at 0.5Hz).
* has much higher torsional stiffness.
* is capable of carrying higher payloads.
* experiences much less yielding (and hence hysteresis) in flexing components.
* has a much larger linear range in bending.

In addition to the structure of the beam itself, we have also dealt with the motor drive and the sensor electronics. Our motor drive has been changed from a conventional DC brush torquemotor to a limited angle, brushless DC torquer. The original torquemotor was saddled with nonlinearities and limitations that tended to mask the effects we are trying to study. In particular, it displayed brush friction, high cogging torque, ripple torque, and brush commutation effects, all of which appeared as relatively high level noise sources. Our new brushless torquer has eliminated all of these effects. Its main friction component comes from the bearings, and this is extremely low.

Another hardware area that required our attention was the development of a suitable target object. We desired to have a moveable target so that we could investigate tracking of a moving object. To keep development costs low, we decided to use an HO model railroad engine as our target. This has proven satisfactory to date. It remains to be seen whether a more sophisticated target will be needed in the future.

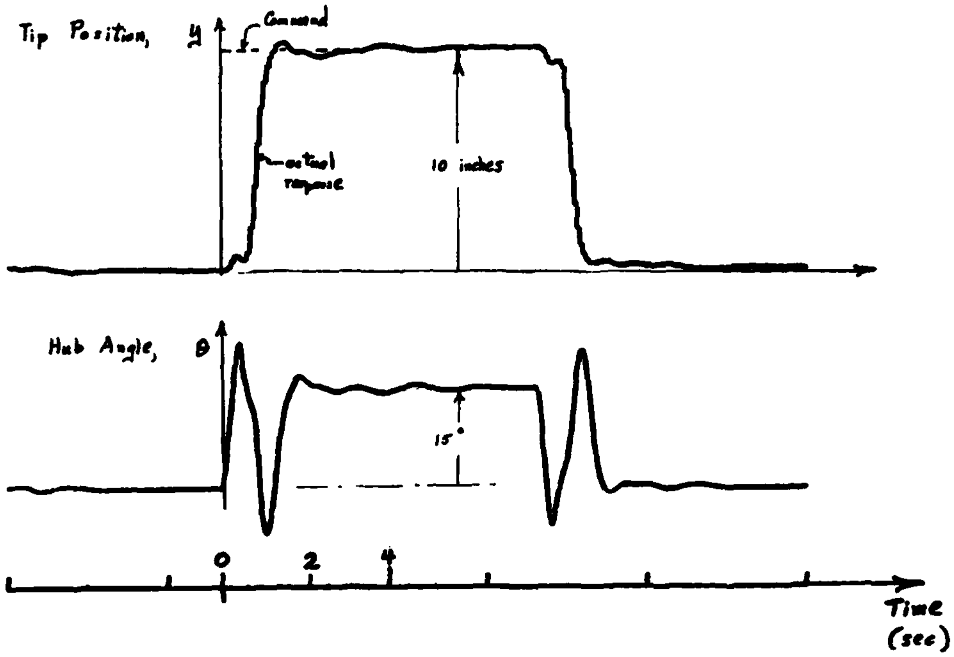
Our final hardware effort, and this has been quite extensive, has been in the support electronics. We have acquired a set of high precision instrumentation amplifiers and connected these to the strain gauges, potentiometers and other sensors on the beam. These amplifiers help minimize drift and reduce noise. In addition, we have developed a set of analog differentiation circuits with which we can derive pseudo-rate signals. These have proven extremely valuable in our control algorithms, especially at lower sampling rates. Finally, we have investigated and developed a number of new end-point sensors for use in our work. The details of these sensors are described under section 4.1.2.

Experimental Control of Position

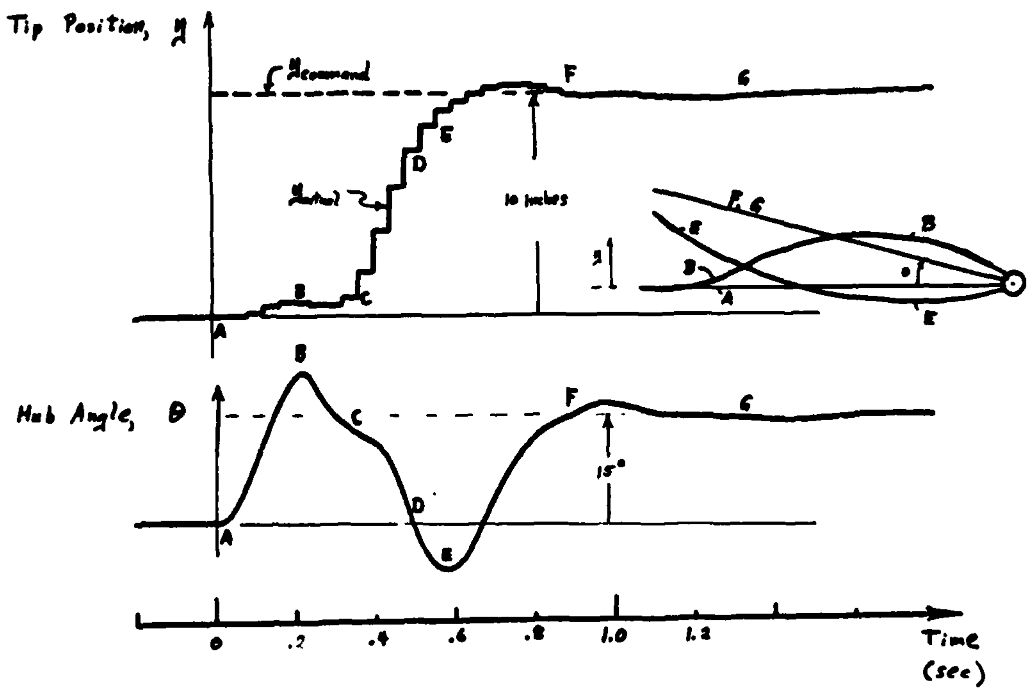
Data from experiments with the very flexible manipulator system of Figs. 3 and 4 are displayed in Figs. 5, 6, and 7. Fig. 5 shows feedback control of end-point position (using optical end-point sensing), Fig. 6 shows control of tip force, and Fig. 7 shows a slew-and-touch maneuver.

Fig. 5(a) shows response of the system to commands to change end-point position. The upper trace shows the step command to a new position 10 inches away, and then another command for the end-point to return to the original position.

To understand the significance of this demonstration, certain background is useful. It is now well known that when one *colocates* the sensor and actuator of a system to control flexible members, it is easy to achieve stable control. (This was first shown at Stanford in 1961, Ref. 4). Almost any control algorithm will produce stability. ***For this reason*** all commercial robots use sensors located where the torques are applied (e.g., at the robot's



(a) Response to Step Commands



(b) Expanded Time Scale

Figure 5. Position Control

joints). This has the disadvantage, of course, that the robot arms (and drive trains!) must be made very stiff, and therefore heavy, to insure that the end points of members can be predicted from the joint angles. This of course imposes a severe penalty in speed and in power required, as well as in achievable precision.

Conversely, sensing end-point position (or force) directly can enable much greater precision and swifter movement with much less power: for the high stiffness requirement can then be waived. But now the control problem — controlling the position of one end of a flexible member by torquing at the other end — becomes very hard; for the many modes of natural vibration of the beam-like members (and drive trains) are now inside the control loop and are each ready to go unstable the instant energy is introduced through the controller. A most sophisticated controller is needed to achieve rapid response to commands without instability.

This is the achievement of Fig. 5. For, as we shall see, not only is the end-point moved in a stable well-damped manner, upper trace, but it is moved in a time comparable with the time it takes a wave to travel the length of the arm! To achieve this, the controller must have the torques move the hub angle (second trace in Fig. 5(a)) through high angles, first to accelerate and then to decelerate the tip. The controller uses only error feedback (no feedforward); but of course the controller contains a high-order model of the arm's bending modes, and thus anticipates its responses.

The performance can be seen in interesting detail in Fig. 5(b) where an expanded time scale is used. Again, the upper trace is tip position (measured optically), and the lower trace is hub angle (measured by an encoder colocated with the control motor). The manipulator configuration corresponding to each time is sketched also in Fig. 5(b). A sketch is also shown of beam configuration as the maneuver progresses. (Angles are exaggerated to make the picture clearer.)

At time zero (point A) a step command is given, upper trace. The motor-and-hub responds almost instantly, lower trace, the hub turning past its final 15 degree position to about 22 degrees. *The tip,* however, responds not at all until t = 0.35 sec. (point C). This is approximately the time for a wave to propagate from the hub to the tip. This represents an *absolute limit* on the minimum time for the tip of this flexible beam to be moved. Between t = 0.35 (point C) and t = 0.65 (point E) the tip is whipped to its commanded position *and held there*. That is, the end-point is put and held in its commanded position in about twice the physical minimum time possible. To accomplish this, the controller has used eighth order prediction (its model of beam dynamics), first to apply high coercion (in the form of a high hub angle) to accelerate the tip (point B), and then to anticipate its arrival at its final desired position and (with reverse hub angle) to put on the brakes, point E. Thereafter (E, F, G) the controller relieves strain energy at just the right rate to avoid moving the tip. (Good feedback control is an elegant thing.)

It is important to point out that this experimental arm is far more flexible (perhaps 100 times more) than an industrial version might be. Thus, to imagine industrial performance of this controller it is appropriate to reduce the time scale by, say ten in Fig. 5. Then one sees that the entire maneuver of precise change in position would be accomplished in 0.1 sec.

Experimental Control of Force

The next demonstration is of the force control that has been achieved. In these tests the force sensor (the "finger" in Figs. 3 and 4) is placed in light contact with the target surface. Then various force levels are commanded, and the controller, using the signal from the force sensor, controls motor torque at the hub to achieve and maintain the commanded force level.

Experimental results are shown in Figures 6(a) and (b), where, in each case, force level (measured by the sensor) is shown in the upper trace, while the hub angle used by the controller is shown in the lower trace. Because the tip is now constrained, the dynamic system in Fig. 6 is substantially different from the free-end system in Fig. 5. The wave propagation time is seen to be shorter, about 0.2 sec, after which the commanded force is established in about 1.5 sec. This is an early force control system, and we expect to improve upon its response speed. But that will take more time. *

Slew-and-Touch

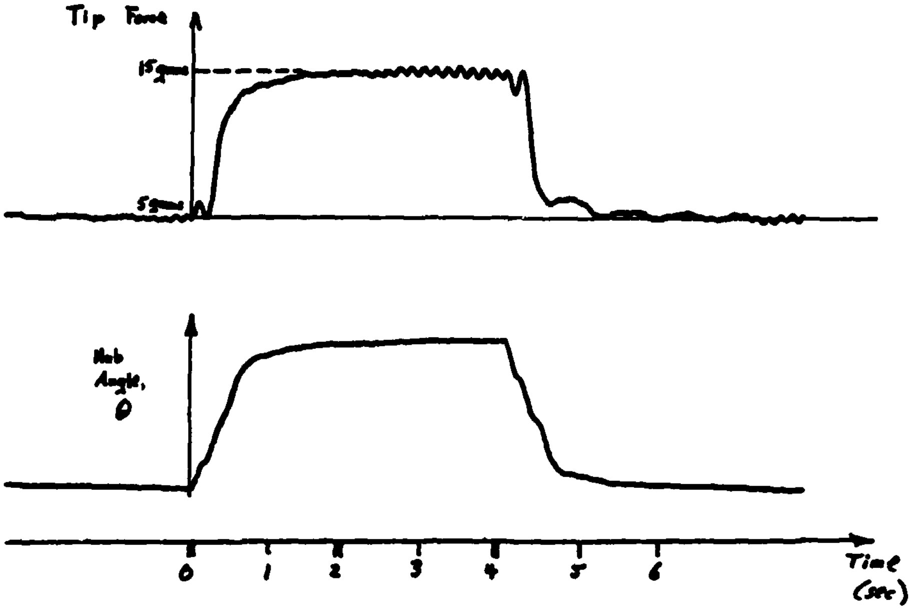
This is a primary goal of our research:

4.1.1.2 "Target object shall be contacted without pause in the motion of the robotic arm."

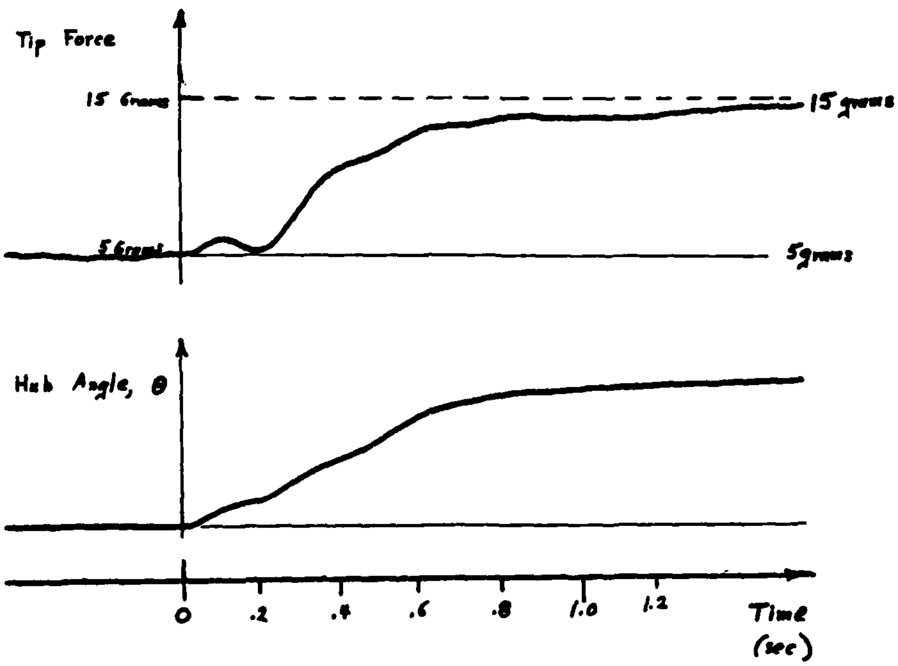
This involves both the control of position and the control of force described above. But it involves also switching smoothly between the two *without pause,* and this itself is not easy; for the dynamics of the manipulator are very different before and after contact, and so are the dynamics of the eighth order controller required to provide good control. Indeed, if the force controller is engaged when there is not contact, the system goes unstable. Commercial robots always make a full stop before making contact. In an assembly operation this is a major time user. For this reason, this task is very important to us.

Our progress to date is demonstrated by the experimental data of Fig. 7. Here all three measured variables are recorded vs. time: hub (and control motor) angle from the encoder, tip position from the LED and photodetector, and force from the force-sensing

* The little early bounce at 0.1 sec. in Fig.6, and also in Fig. 5, is due to an anomaly of the instrumentation: The optical and force sensors are mounted on a plate between the two beams that make up the manipulator arm, (see Fig. 4), so that when the hub rotates, one beam is shortened and the other lengthened, which rotates the plate and moves the sensors even though no lateral displacement of the beams has yet occurred.



(a) Response to Step Commands



(b) Expanded Time Scale

Figure 6. Force Control

finger. Also shown on Fig. 7 is a drawing of beam configuration as the maneuver progresses.

Again, it is quite instructive to follow the maneuver move by move. At A, the tip is commanded to proceed to the point where it will just contact the target, some 10 inches from it. The command used is not a step, in this case, but an exponential that is asymptotic to the target position (like the flare path for a landing aircraft). The hub moves at once, A, to initiate a fast slew of the arm. At C, the wave has propagated to the tip, and the tip begins to move. * At D, the controller, anticipating impending arrival of the tip at the target, reverses hub angle to "put on the brakes". (In the photo of Fig. 4(a) the system is just at D.) At E, the tip has arrived at the target, and contacts it without pause. The controller switches to force control at this instant (using a fiber-optic indicator of impending contact), and then carefully rotates the hub the additional 4 degrees necessary to establish the commanded force level of 10 grams.

To the eye watching the manipulator tip, this process is quite impressive. It is quick, smooth, and contact is made without interruption. The force signal reveals some small oscillation of the force sensor itself (the "finger") as force is building up.

Again, it is important to point out that this experimental manipulator is much more flexible — e.g. 100 times more — than a commercial version would be. Thus in thinking of performance in a factory it is appropriate to reduce the time scale in Fig. 7 by, say, ten. Then the entire process shown in Fig. 7 — slew through 10 inches, contact target without stopping, and apply force — would be completed in 0.4 sec.

Our ultimate goal is to perform the slew-and-maintain-force maneuver on a moving target. (The target position signal was used by the controller in Fig. 7. It is a good clean optical signal just like the manipulator tip signal. In the maneuver of Fig. 7 it did not change because the target did not move.)

Before proceeding to the moving-target problem, however, we plan first to investigate other aspects of our slew-and-touch results:

4.1.1.3 "For a given allowable force level, the velocity with which the arm can contact the end-point will be increased by a factor of ten (10)."

We need to study commercial robot behavior to see by how much we can exceed this goal.

4.1.1.4 "Tolerable time delays in system response shall be identified."

We have made some investigations in this area, but have not formalized our findings. One of our main results is that the time delay associated with the wave propagation along the length of the beam defines the absolute limit to possible performance, as noted earlier (Fig. 5).

4.1.1.5 "Required bandwidths for system components shall be defined."

Here we have found that achieving a closed-loop bandwidth approaching the first flexible mode of the beam is the practical performance limit. For best performance, sampling rates must be high enough so that the Nyquist rate is above the highest significant bending frequency (i.e., the sampling rate must be at least twice the highest bending frequency).

* Again, the small wiggle at B is an anomaly of the instrument mounting on the experimental beam.

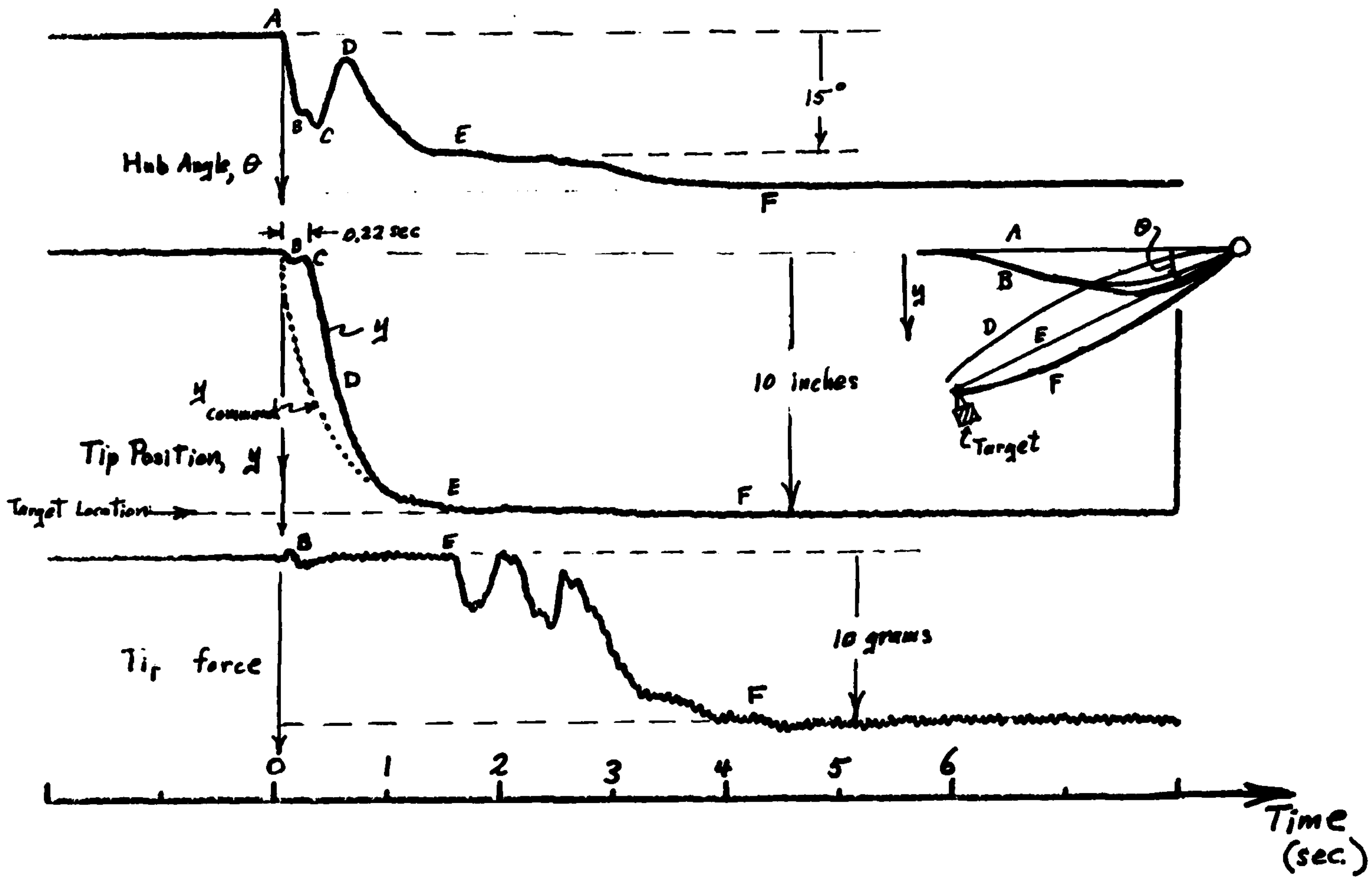


Figure 7. Fast Slew-and-Touch.

Our typical control loops run at a data sampling rate of 25 Hz, which is 3 times our highest significant mode. Values of 3 to 10 times the highest mode seem reasonable.

Task 2: Position and Force Sensor Development

4.1.2.1 "Position sensors, such as X-Y photodetectors, shall be developed to provide gross position determinations."

Much effort has been spent in this area, and the results have been very encouraging. We have successfully developed an optical end-point sensor that can, potentially, track up to 8 targets in real time. Currently, we have implemented the version shown in Figure 4 which senses two positions (arm tip and target) simultaneously: the precision of this sensor is approximately 0.01 inches over a 20 inch range, and it has a bandwidth of 10 Hz. It works by using an X-Y photodetector to sense the location of small light emitting diodes (LED's) which are attached to the object to be sensed (Fig. 4(b)). Blinking the LED's on and off during successive time intervals allows the detectors to track multiple objects.

The development of this device has provided us with a precision end-point sensor and has allowed us to pursue the slew-and-touch task as well as the task of real time tracking.

4.1.2.2 "Force sensors, such as strain-gauge-equipped 'fingers' shall be developed for fine position determinations. Possible use of proximity sensors shall be investigated."

We have developed and have operational the force sensor described above and shown in Fig. 4. It is being used to sense the contact force exerted by the tip of the beam on the target object. We also have in the lab a proximity detector of the type used industrially to sense metallic objects. We are investigating using this sensor during the instants just before and after contact is made with the end of the beam.

4.1.2.3 "The sensors shall be integrated into a control system and optimized to provide precision end-point sensing in conjunction with Task 1."

This has been accomplished both for the photodetectors and the force sensing finger. We are still investigating whether a proximity sensor will be a useful device to us.

Task 4: Switching Between Control Regimes

4.1.4.1 "Algorithms shall be developed to allow for smooth switching between control modes (i.e., gross control vs. fine control) while the arm is in motion."

Our first attack on this problem has been quite successful, as demonstrated in Fig. 7, where a smooth switching from fast position control to force control is accomplished. We need to generalize the capability and develop the underlying theory to a degree that is more generic.

We are developing our control algorithms by using optimal control techniques to derive Kalman filter estimators and full-state-feedback control laws.

4.1.4.2 "The algorithms shall be capable of sophisticated slew-and-touch control of the arm designs from Task 3."

The first arm design of Task 3 has just been constructed, and we have not yet accomplished sophisticated control of it.

*Task 3.*Investigate New Robotic Arm Designs

4.1.3.1 New arm designs shall be optimized for decreased weight and increased terminal velocity.

4.1.3.1.1 An arm design with a minimum of two revolute joints shall be investigated.

4.1.3.1.3 Methods of adding flexibility to the arm shall be investigated.

4.1.3.1.4 The impact of mass distribution on arm response shall be investigated.

The first robotic arm designed and built under Task 3 is a two-link rigid arm with flexible tendon drives. It is shown in Figures 8 and 9. Its design, construction, and preliminary testing were supervised by Michael Hollars.

The arm was designed to have minimum weight, yet be very stiff, by using aluminum tube and shell construction. Increased terminal velocity was achieved by penalizing mass distribution as a function of distance squared from the innermost joint (shoulder joint), since the effective inertia seen by the drive motors is mass times distance squared.

Further design features include:

1) Payload to arm mass ratio of about one. This demonstrates a wide range of vibration modes which the control system must accommodate. The maximum vertical sag when fully loaded is about 1 mm (0.04 in.) and the structural modes of the links are well below (a factor of at least four) the flexible modes of the tendon drives.

2) The arm geometry is designed such that the arm has a one meter (39.37 in.) maximum reach and a half meter (19.7 in.) minimum reach from its attach point on the base. The shoulder joint has a range of ± 90 degrees and the elbow joint has a range of ± 120 degrees.

3) The motors and gearing were sized such that the unloaded arm with nonflexible tendons can move between any two points in its operational envelope within one second (starting and stopping with zero velocity). For a one meter (39.37 in.) arm this gives maximum accelerations of about 13 m/sec (1.32 "gees") at the tip.

4) The drive motors used are 1.41 hp printed circuit motors manufactured by PMI, Inc. Since there is no ferrous material in the armature, there is no cogging torque and ripple torque is minimized. Thus the drive motors are very linear and can be used with low gear ratios.

5) The shoulder and elbow drive motors are geared 6.25:1 and 2.5:1 respectively and both can generate up to 3.7 Newton-meters (528 oz-in) continuously and 11.1 N-m (1583 oz-in) peak for 0.5 sec using the power amplifiers supplied by PMI, Inc.

6) The vibration frequencies are adjustable by the use of replaceable linear springs in the tendon drive system. The system currently has springs with spring constants of 688 kg/m (38.5 lb.in). The vibration modes of the system with these springs, arm unloaded and links parallel are approximately 10 Hz and 15 Hz.

7) A rigid concrete base weighing 1000 Kg (2200 lb) is used to eliminate any base vibrations or motion. The arm and drive system is secured to the concrete base with a 19 mm (.75 in) thick aluminum plate. The aluminum plate can be tilted 15 degrees so that a 25% component of gravity can be added.

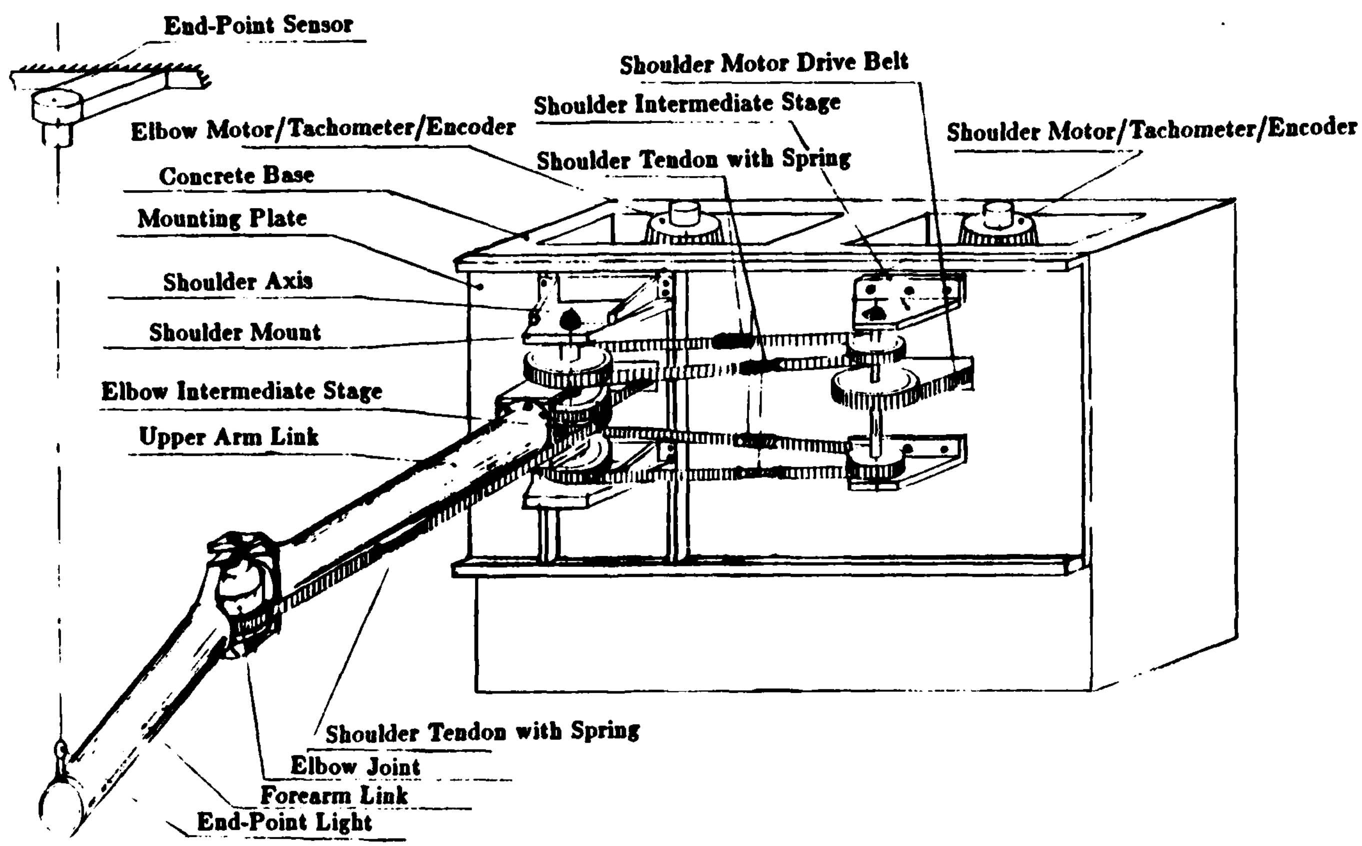


Figure 8. Two-Link Arm with Flexible Tendons.

8) An electronics rack has been built to house the motor power amplifier, sensor electronics and computer i/o interfaces. Extensive safety electronics has been designed and built to allow quick stopping of the arm in case of computer failure, intermittent power failure or imminent harm to equipment or people.

9) The arm is currently designed for 10 sensors. Each motor has an 1800 line incremental optical encoder for position sensing. The associated electronics has been built and installed in the electronics rack. Each motor also has an analog tachometer for rate sensing. Soon to be added are optical encoders on the joints themselves for position sensing, rate sensors on each joint (type yet undetermined) and an optical X-Y position end-point sensor (similar to that used on the one-link flexible arm).

10) A PDP 11/24 with hardwired floating point was purchased for the control computer. The computer has been installed and is operating under RT-11. Additional peripherals added include a real-time clock, an analog-to-digital conversion board with MUX expander for a total of 32 differential channels, a digital-to-analog converter with four channels, a digital i/o board, an eight channel asynchronous communication board and an IEEE 488 bus board.

11) The software written thus far includes device drivers for the clock, A/D's, DAC's, and IEEE 488 board; colocated closed loop control law for the two-link arm using the motor encoders and tachometers as sensors; and various testing routines.

Figure 9 is a photograph and Figure 8 a detailed isometric drawing of the two-link arm with the major components noted.

Testing of the arm revealed that alignment of the bearings in the elbow joint were not accurate enough. The joint began to stick after less than a thousand cycles. The solution is to use bearings which can withstand larger misalignments and to redesign the elbow joint yoke to be stiffer. Two different belts for the tendon drive were tested for strength and linearity for a wide range of spring preload. The belt with less hysteresis and higher failure loading was selected for use. The report is appended.

This two-link arm is now constructed and preliminary tests have been completed. It represents a major new facility for us which was made possible by this DARPA funding. It approaches industrially interesting configuration with its multiple links, lightweight (but stiff) construction, and drive-train flexibility that we hope will be stimulating to designers of the next generation of robotic systems.

Later in our program we plan to demonstrate an array of manipulator-control technologies with this facility, which will be an important step closer to industrial adoption.

At this point, as agreed in early discussions with our DARPA and AFOSR sponsors, the facility will be dedicated for a time to preliminary studies of a basic nature under AFOSR funding.

Intelligence and Dexterity in Hand Control

The three finger hand

A three finger hand was designed and fabricated by Salisbury under a joint Stanford-

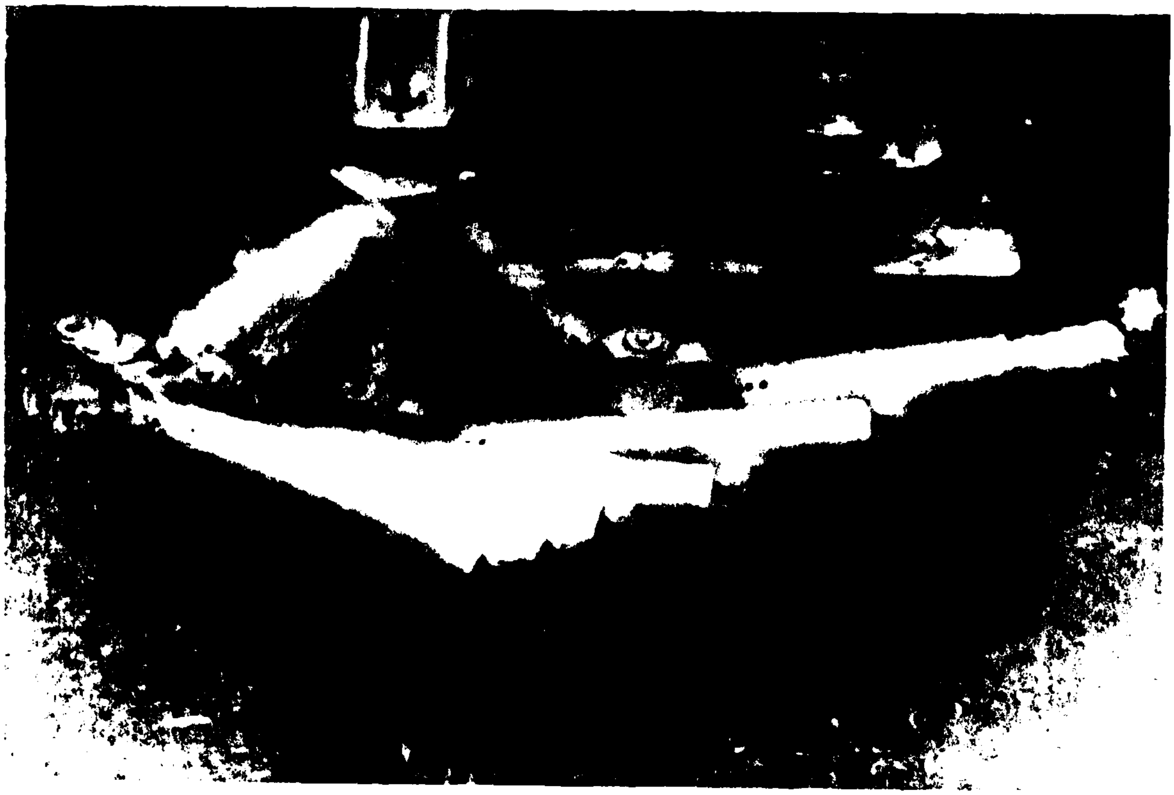


Figure 9. Experimental Two-Link Arm with Flexible Tendon Drive.

Figure 10. Photograph of the Hand

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JPL project funded in part by the President's fund at JPL. Figure 10 is a photograph of the hand. Research was continued under support by the National Science Foundation, including part of the assembly, interfacing a single finger, analyzing control algorithms, designing them, and partially implementing them. Fabrication was completed under this contract and mechanical modifications were made.

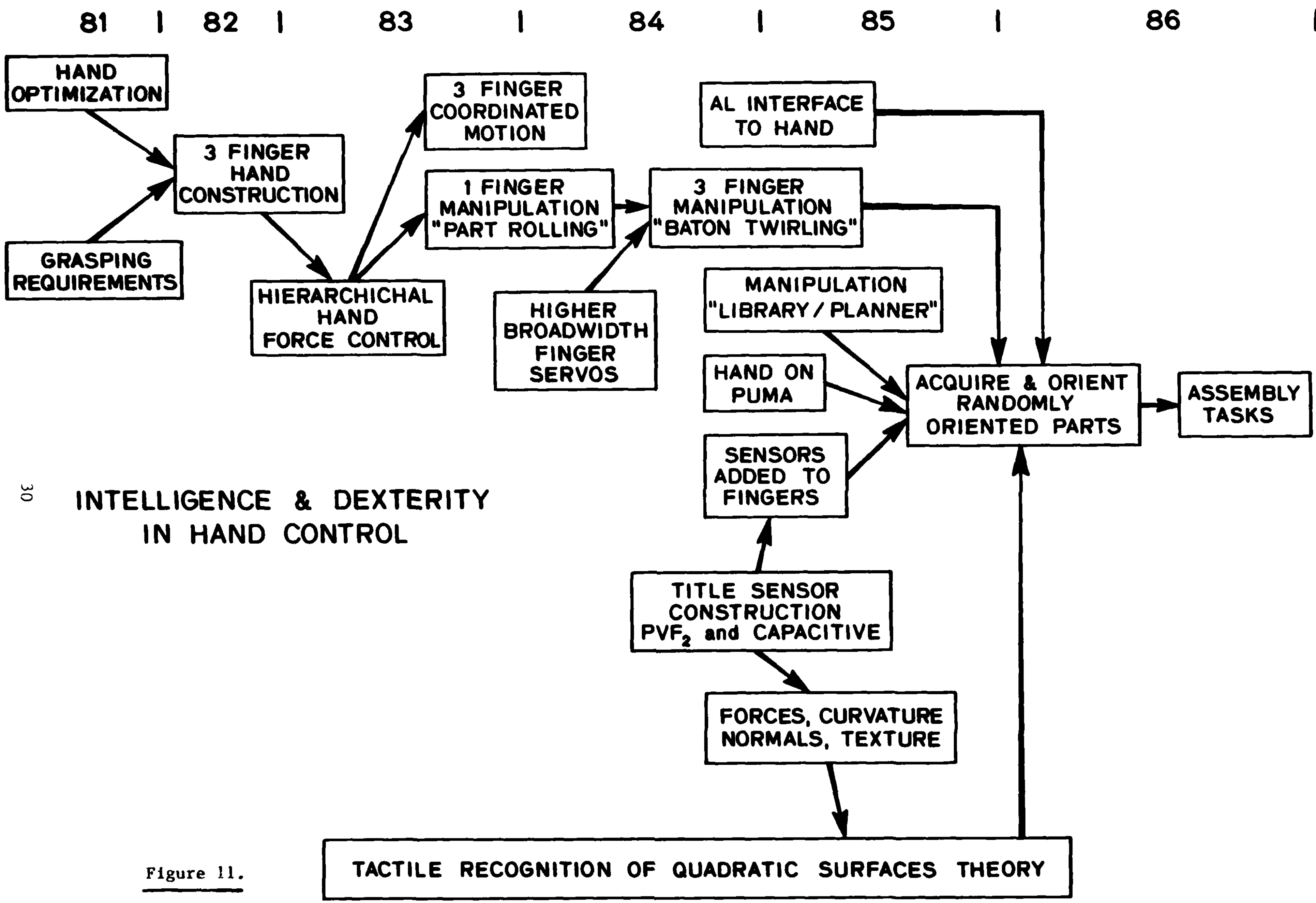
In the design of the hand, Salisbury made a complete kinematic analysis in order to choose a necessary and sufficient configuration for complete repositioning, i.e. general translation and rotation [Salisbury 81]. Salisbury designed a hand that meets two goals. The first is that when the finger joints are locked, the object is completely restrained in the kinematic sense, that is, the object can resist arbitrary forces without motion. The second goal is that with joint motion, it is possible to apply arbitrary small forces and cause arbitrary small motions of a grasped object.

Five different contact types between a finger and object were examined, but the point contact with friction was chosen, because friction is necessary to restrain objects like cylinders and spheres. The point contact with friction has three degrees of freedom (rotations) about the contact point. Three fingers with three DOF each were chosen. The combination of 9 DOF of finger motion with 3 DOF point contacts gives a hand that has excess constraints on the object, which allow control of internal as well as external object forces. This excess constraint is important for keeping frictional constraints active. Nine degrees of freedom were necessary under the conditions chosen.

Link lengths and finger placements were chosen to optimize the reachable workspace volume, keep singularities out of the workspace, and minimize the effects of errors in joint angles and error propagation by operating where the Jacobian matrix of the fingers is well conditioned. A nominal object (1 inch sphere) was used to guide the design. An optimization program, OPHAND, was developed to optimize hand parameters based on maximum working volume with finger tip manipulative grasps. The program searches up to 5 parameters simultaneously of the 36 dimensional hand parameter space. This volume optimization was done while maintaining certain desirable features, such as the ability to do power grasps (fingers curled around object), and having a palm to use as a grasping surface.

Concern was directed to limits of force control imposed by the kinematic design. The condition number of the Jacobian matrix was introduced as a measure of the sensitivity of forces exerted by the hand relative to the forces controlled at joints of the fingers. Salisbury extended the idea of a Jacobian matrix, which usually map torques in joint space to forces in cartesian space, to 3 fingers simultaneously grasping an object. This is called the Grasp Matrix, and maps fingertip forces to the external and internal object forces. It can also map finger tip velocities to grasped object velocities. The grasp matrix can also be used to give the grasped object any desired stiffness behavior in cartesian space.

The Stanford-JPL hand was constructed with a tendon drive system. This allows the mass of the motor system to be located away from the end of a robot arm, increasing payload capability. It is also necessary to keep the fingers small. In order to minimize friction and thus improve controllability, a pull-pull tendon design was chosen. In a straightforward design, that meant two motors per degree of freedom. Salisbury discovered that tendons could be coupled in such a way as to require n+1 instead of 2n motors, four for each finger



INTELLIGENCE & DEXTERITY IN HAND CONTROL

Figure 11.

instead of six, a total of 12 motors in all. High performance DC motors drive a gear box that pulls on the tendon. The finger positions are inferred by measuring motor rotation and estimating tendon stretch.

The tendon tension is measured by a strain sensing element mounted on a beam at the finger end of the cable. This means that the major sources of friction- motor, gears, and tendon sheath, are before the sensor, so a control loop can be used that reduces the friction effects.

Under this DARPA contract, the entire hand was assembled and the tendons were installed. Mechanical modifications to the hand were made. A modification was made to the tendon sheathing material so that a teflon liner could be installed in all the sheaths.

Two Unimation 260 robot controllers were purchased to control the tendon motors. These controllers contain encoder interface circuits, DC motor drivers and a microprocessor for each motor. They do not contain the LSI-11 for VAL since it is not necessary for our purposes. Two of these controllers are required to control the 12 motors of the hand. Burdick designed and built an amplifier interface board which is used to amplify the tenson sensing strain gauges.

Hierarchical Force Control

We developed an elegant and general system for specifying force control tasks for coordinated motion of complex hands [Salisbury 81]. Usual control schemes are formulated as position control in joint coordinates. Ours is a cartesian force control scheme which is hierarchical in three levels, the hand level, the finger level, and the tendon level. Figure 11 shows the structure of the control scheme.

The hand level specifies the task in object terms, i.e. specifying position and velocity of the object and specifying forces on the object. This is a natural form for planning operations to specify. At the highest level, three finger controllers are used together to apply coupled finger forces to achieve desired object stiffness and velocity in cartesian coordinates. The top level control system is show in Figure 11. The intermediate level finger control is cartesian force control of four tendon control loops. Tendon control is tension control of a single tendon.

Craig implemented the control system for three fingers. By the end of the first year, almost all code had been written. Soon into the second year, motion of all three fingers was demonstrated. Although not quite in the time frame covered by this report, the hand first became completely operational with all three fingers moving in coordination on November 11, 1983.

The code was optimized for speed. To increase the speed of computations fast arithmetic routines were written in assembly code to be PASCAL callable. This provided us with very fast SQRT, SIN, COS, and ARCTAN routines. The PDP 11-45 operating system was reconfigured so that the programmable clock could be used to generate timing ticks for servos.

In order to control the 3-fingered hand, many different processes need to be handled at varying rates. A "scheduler" was written which allows routines to be run at any of 3 levels - servo level, background, and intermediate level. The servo is triggered by interrupts from the programmable clock (now set for 150 Hz). A 12-tendon servo routine was written for fast execution. It requires 4.6 ms to do the servoing of all 12 tendons. It accomplishes the lowest level of the hand control by controlling the tension in the individual tendons.

Along with Cartesian force based control of the fingers [Salisbury 81], a new "joint-based" control algorithm was added to the control software. The ability to run the fingers in different control modes will be used to evaluate potential control schemes. A simple cubic-spline path generator was written to demonstrate the new joint-space motion control mode.

Auto-calibration software was added to the system so that the fingers could calibrate themselves at startup. The tendons are pulled tight and then the fingers are moved so that the joints move to their limits and are held there while the encoders are set to the appropriate values.

A videotape was made of three aspects of operation of the three finger hand, i.e. coordinated motion of three fingers, auto-calibration, and rolling an object.

Substantial effort has gone into bringing the PDP 11/60 on stream. It suffered from several nagging problems including disk problems and memory problems. These problems persist into the second year. Increased computational power is important to task execution with three fingers in coordinated motion. The PDP11/60 has been tested on several benchmarks and found to average almost exactly twice as fast as the PDP 11/45 for floating point computations. Although the hand was not controlled by the 11/60 by October '83, we hope to eventually move the hand to this machine in order to take advantage of the increase in computational power. Happily, no rewrite of software will be necessary at all.

High Level Software

Work was done in laying out how the hand software will be interfaced to the AL system. One concern is making software transportable across a number of machines. In part this is aided by an implementation in PASCAL. However, PASCAL is somewhat implementation-dependent, and our software is dependent on the operating system. We are evolving towards a distributed system linked by the Ethernet. The hand software will reside on a dedicated machine connected to the local ethernet. In a message format that we have designed, other machines on the net will be able to command hand motions and sensing with a variety of commands. A separate machine running AL will most likely be the generator of these messages, though the interface will be general enough that the hand will not be restricted to using AL as a front end.

Strategies of Grasping

A new project was begun in manipulation of objects using the three finger hand. Fearing analyzed rolling a part between fingers then began an implementation of the algorithm in Pascal on the PDP 11/45. This research led to manipulation of an object in the hand soon after the end of the first year, after the time period of this report. The task was rolling a pillbox between one controlled finger of the hand and one fixed, external finger. The goal of this work was to show the feasibility of using fingers with stiffness control and slip to manipulate small parts in a hand. The study concerns grasping of objects without good object models [Fearing 84]. The design of fingers covered with compliant material is being investigated.

A grasp is considered stable if the grasping force can be increased to prevent slippage due to an arbitrary external force. One investigation seeks to determine all possible grasps for two parallel jaws with slight friction and ignoring torque. Fearing investigates the class of parts with arbitrary cross section, straight generalized cylinders with constant cross sections. This becomes a two dimensional problem for an arbitrary curved cross section grasped by two parallel jaws.

Identifying Objects and Locating Them by Grasping

This study uses sparse tactile data, three data points, one from each finger. At each finger, position and surface orientation are measured with some known accuracy. The goal is identify object and orientation in natural, rapid motions, without multiple grasps, feeling, or groping. Clearly improvements can be made in sensing available to the system, especially pattern touch.

Goering is designing and building a system to identify objects and their orientation from object model represented as volumes bounded by a subset of quadratic surfaces, which represent elements of planes, cylinders, cones, and spheres. The system requires far fewer patches than systems with polyhedral modeling. Since many algorithms require combinatorial search, the representation gives a potential benefit in computation. Considering faces pairwise, constraints between points on the faces can be determined, especially bounds on the distance between pairs of points. Stronger constraints involve the relationship between two arbitrary surface normals and their skew.

Model selection will proceed by determining skew relationships for each pair of data points, three pairs. These relationships will be compared with triples of faces to find skew relationships with acceptable fit. Possible interpretations may be ordered according to best fit. Then a point can be tested further to determine whether the point lies on a given surface.

The modeling system was designed and implementation had begun during the first year of the contract, the period of this report. Investigation was done concerning the matching process and a preliminary design was made.

Sensor Design and Fabrication

The hand itself has tension sensors on all tendons. Its joints are tension controlled.

A finger force sensor was designed by Yoram Kirson under AFOSR support while

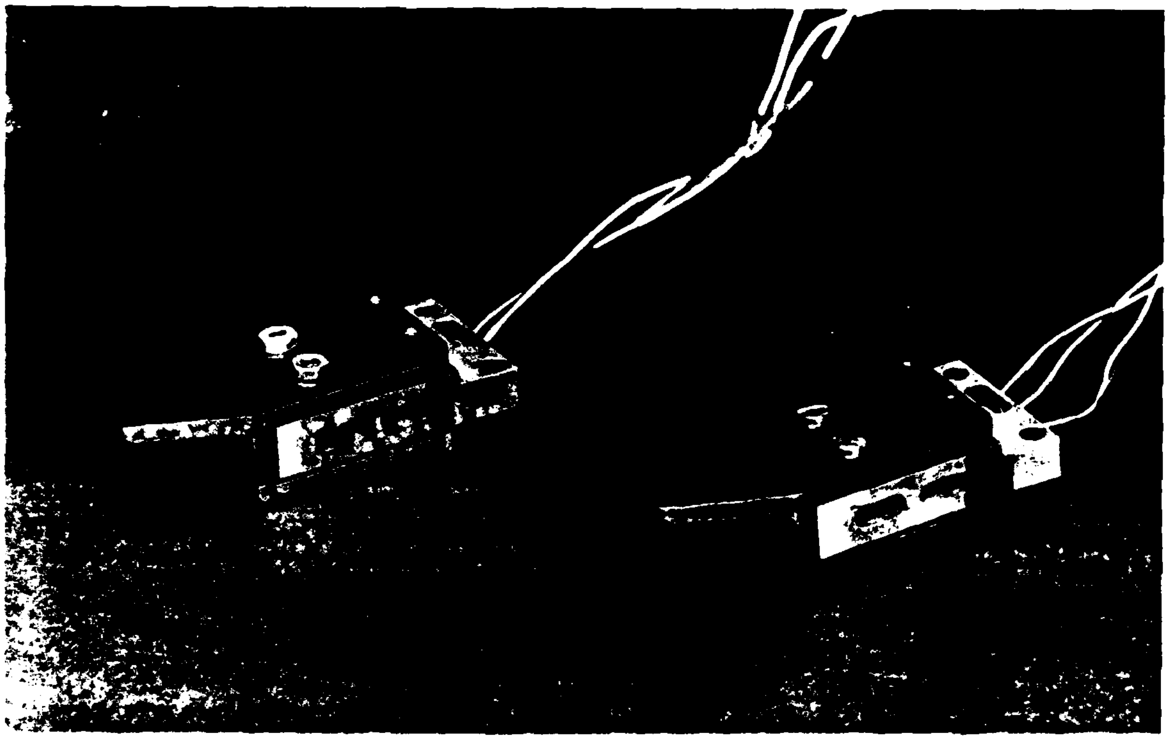


Figure 12 a) Photograph of the Finger Force Sensor - top view

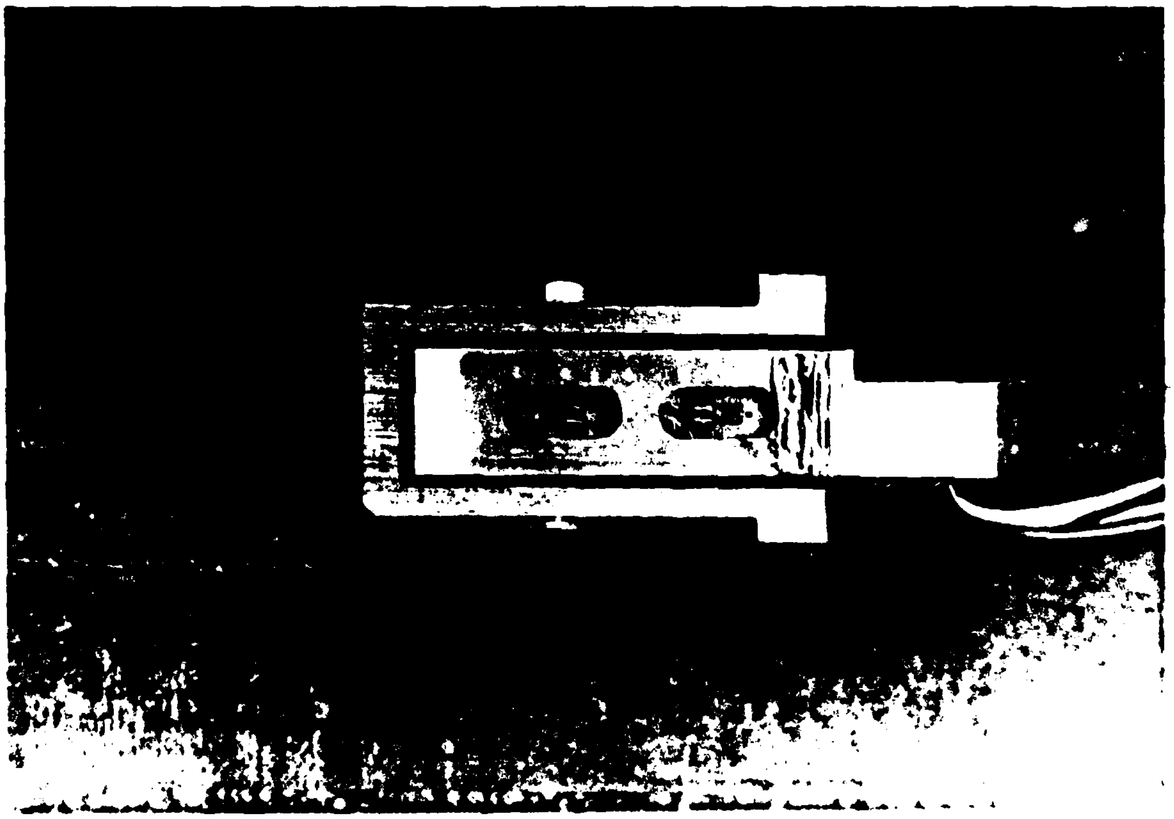


Figure 12 b) Photograph of the Finger Force Sensor - side view this contract was delayed [Kirson 83a]. The project was transferred to this contract. Aspects of the design related to fabrication, and the bulk of the fabrication were done under this contract. Figure 12 is a photograph of the finger force sensor. The project was transferred to the Intelligent Task Automation project, a collaboration under subcontract to Honeywell. Mounting strain gages on the sensor, testing and demonstrating it, and software development for the sensor have been under ITA which continues to support software development.

The sensor measures three components of force, x, y, and z components. It is designed for 1 gram sensitivity or less, with most concern for sensitivity to low force range. It has an interesting design of three nested parallelograms, each of which measures one component of force. It is manufactured by EDM, discharge machining.

Another finger force sensor was fabricated. It had been previously designed. The sensor also measures three components of force, also at the range of 1 gram sensitivity.

During the second year, Fearing has begun investigating PVF2 piezoelectric polymer touch sensors. An array of 10 such sensors would provide measurements for an analysis of strain patterns [Fearing 84] and for texture measurement on a surface. Another investigation of piezoelectric devices is ongoing.

We interact with other groups at Stanford involved in sensory technology, including Professor Meindl who is developing capacitive array sensors as part of the AFOSR center, with Professor Linvill who is developing PVF2 sensors. We have discussed the problem with Dr. Barth, who has begun another sensor effort. All these methods have the attraction of utilizing integrated circuit techniques. Our role in these efforts may involve small collaboration, but primarily the quick application of devices as they become available.

Micromanipulator

Yoram Kirson made a conceptual design of a micromanipulator intended for rapid fine motion and force control [Kirson 83b]. The micromanipulator has three degrees of freedom with range about 1 cm on each of x,y,z axes. Figure 13 shows a drawing of the micromanipulator conceptual design. This device provides a mechanism complementary to the hand for fine motion and force control. The project has subsequently been shifted to ITA.

System Support

Design and development was begun for an electronic interface from the three finger hand to control computers. It was also intended for subsequent experimentation with actuators and tendons as components of advanced hands and as a general experimental interface. It became possible to buy an interface with twelve channels from Unimation West under a special arrangement. We decided to get the two Unimation interfaces. That took the pressure off development of the controller and development lagged. Since then, Unimation West has spun off as a robotics startup, Adept Technology. We can no longer

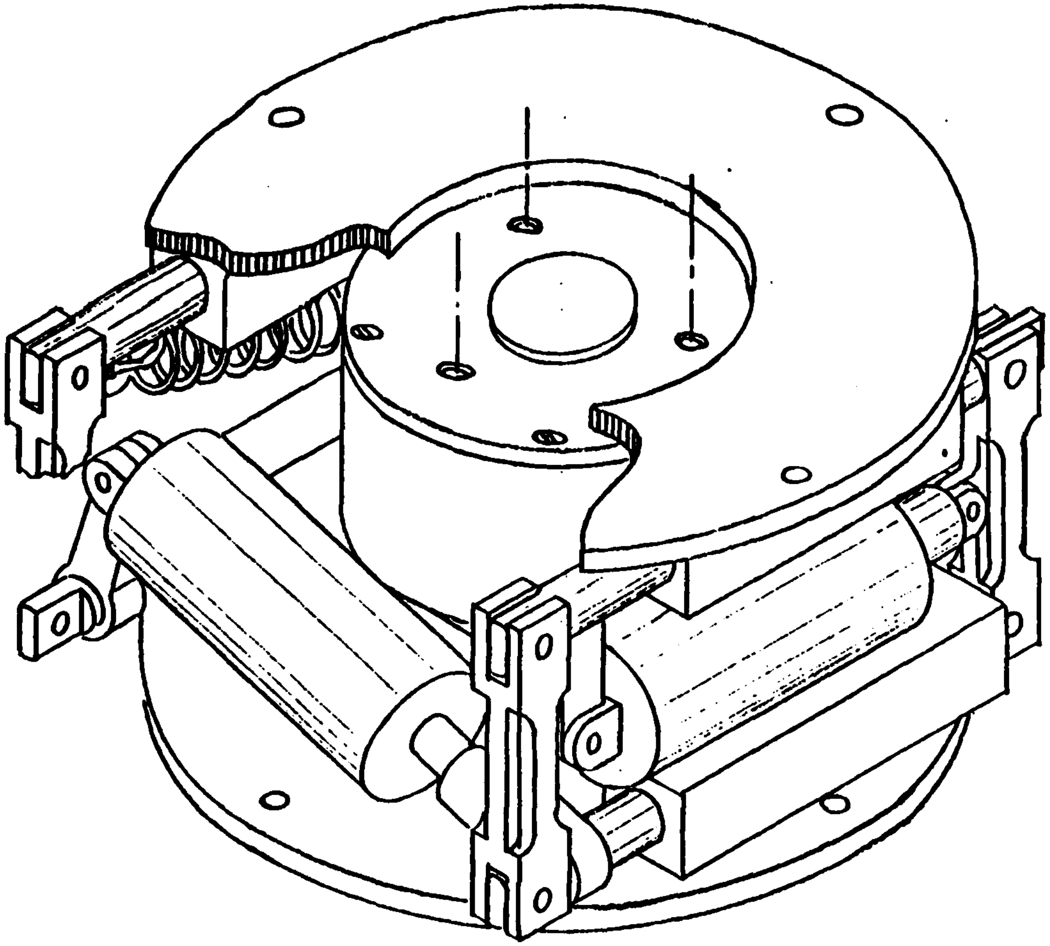


Figure 13 a) Drawing of overhead view of Micromanipulator Conceptual Design.

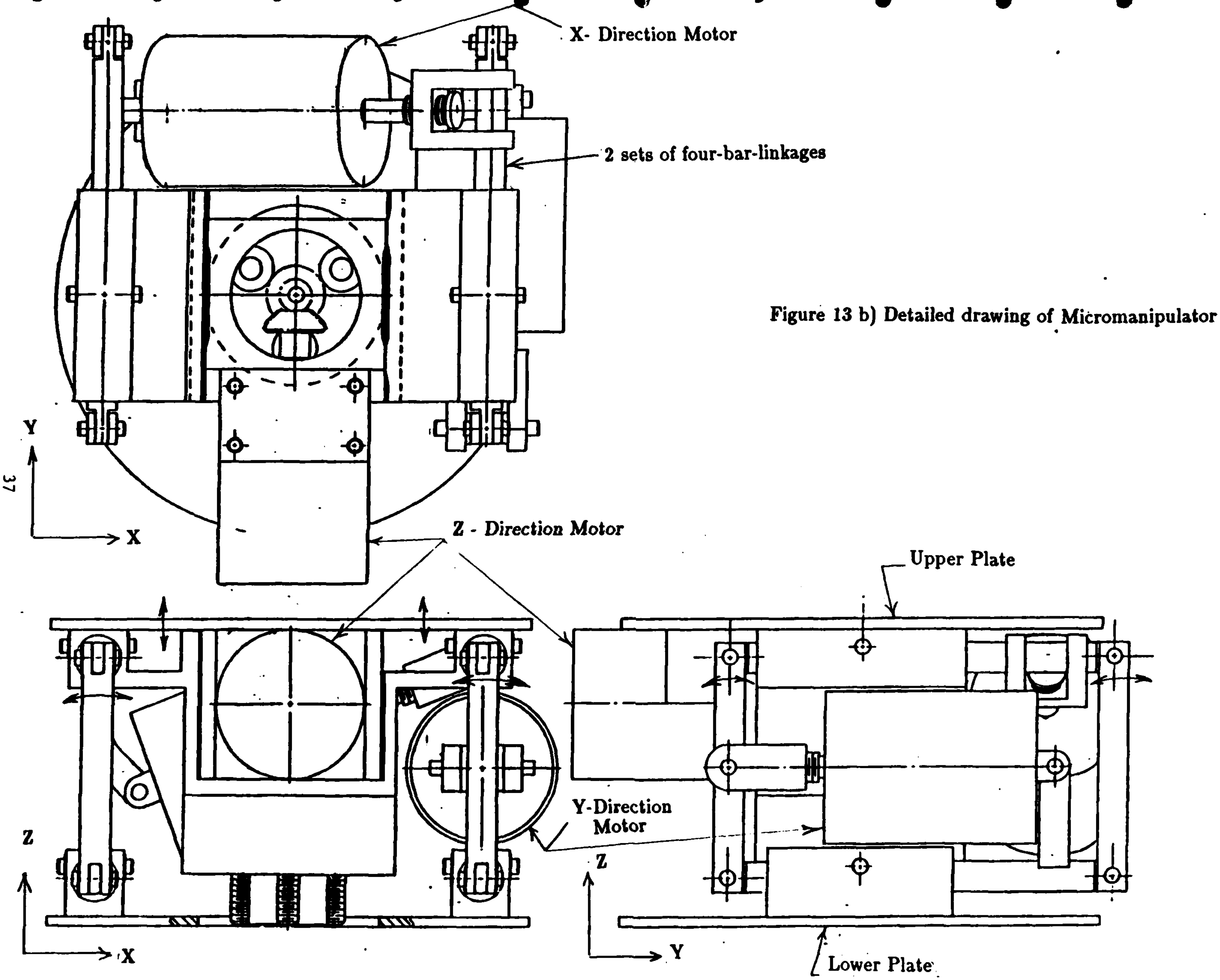


Figure 13 b) Detailed drawing of Micromanipulator depend on special arrangements with Unimation West or Adept Technology for interfaces for subsequent experimentation. Development has continued on the controller. Completion is expected in the second year.

Summary of Projects

This section summarizes our progress compared with the tasks detailed in the contract.

In brief, of 100 points below for nine tasks, in year one 56 points have been achieved vs 34 scheduled. All other tasks are in good shape.

Task 1, to design and construct the hand, is complete.

Task 2, develop and implement tendon motor control loops, is complete. There may be additional improvements in compensating for static friction and dynamics.

Task 3, implement existing force and tactile sensors, is continuing with results already demonstrated.

Task 4, develop and implement preliminary single finger control system, is complete, although an evaluation of control methods remains to be done.

Task 5, develop and implement interactive finger (hand) control subsystem, is complete at the control level. Task 5.2, develop a simplified model to estimate from sensors both local and gross surface curvature and orientation relates to the intelligent aspects of sensory control in task 7. This work is underway.

Task 6, investigate extending beyond trip prehension to re-orienting objects, is underway. Task 6.2, optimize kinematics of hand design, is completed.

Task 7.1, develop software in a manipulator language for programming hand tasks, is underway.

Task 7.2, use of sensor estimates as geometric constraints with manipulation rules in an intelligent system is underway with the work of Fearing without models, and Goering, with models.

Task 8, integration with vision and range sensing, is not yet underway.

Task 9.2, assess integration of hand with a commercial manipulator, is a task for the third year.

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